TITLE

Method and System for Cooling Electronic Components

BACKGROUND

[0001]   Computers and other electronic devices contain numerous electronic components such as processors, memory and graphics products, and other integrated circuits (ICs) that give off heat. Most electronic components are heat-sensitive and may malfunction or become physically damaged if they become too hot. However, the heat threshold within which each component in a given electronic device can safely operate varies from component to component. Thus, system level cooling elements as well as cooling elements attached to individual ICs within an electronic device are vital to the functionality of many electronic devices. These cooling elements may be heat spreaders, fans, blowers, heat sinks, and others.

[0002]   Some cooling elements can be controlled manually or by a control system that is part of an electronic device. For example, a fan can be controlled to operate at varying speeds. Controllable cooling elements are advantageous in many electronic devices because they save power and reduce overall system noise by not always operating at full speed.

[0003]   Some electronic devices rely solely on system level cooling elements for their thermal management. In many electronic devices, however, system-wide cooling requires expensive and space-consuming overhead. Thus, in many instances, individual cooling solutions for some or all of the ICs within a particular electronic device are more efficient, require less space, and are less expensive than a system level cooling solution.

[0004]   Most thermal control systems that are controllable are based on the temperature of the ICs that they cool. For example, a fan's speed may be increased if a particular IC's temperature rises to an undesirable level. However, a thermal control system that is based solely on an IC's temperature is sometimes inaccurate, inefficient, and unable to recognize and react to certain trends in the IC's power usage.

SUMMARY

[0005]   A localized system for dissipating heat generated by an electronic component includes a controllable cooling element and a control system for controlling the

cooling element. The control system adjusts a speed of operation of the cooling element in response to variations in power consumption of the electronic component.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006]   The accompanying drawings illustrate various embodiments of the present invention and are a part of the specification. The illustrated embodiments are merely examples of the present invention and do not limit the scope of the invention.

[0007]   Fig. 1 shows an exemplary integrated circuit configuration with a cooling element according to an embodiment of the invention.

[0008]   Fig. 2 shows an exemplary thermal control system according to an embodiment of the invention.

[0009]   Fig. 3 illustrates an exemplary implementation of the control system using a microcontroller according to an embodiment of the invention.

[0010]   Fig. 4 is an exemplary configuration illustrating how the control system may be implemented in a system level cooling solution according to an embodiment of the invention.

[0011]   Fig. 5 illustrates how more than one control system and cooling element may be used in combination with a system level cooling solution according to an embodiment of the invention.

[0012]   Fig. 6 is a graph illustrating power consumption by an integrated circuit for which a control system could be created or programmed to have memory according to an embodiment of the invention.

[0013]   Fig. 7 is graph illustrating power consumption by an IC for which variations in the power consumption may require the control system to selectively ignore variations in power consumption according to an embodiment of the invention.

[0014]   Fig. 8 is a flow chart illustrating a possible method of implementing the present control system with memory according to an embodiment of the invention.

[0015]   Fig. 9 is another flow chart illustrating a possible method of implementing the present control system with memory according to an embodiment of the invention.

[0016]   Throughout the drawings, identical reference numbers designate similar, but not necessarily identical, elements.

DETAILED DESCRIPTION

[0017]   A method and system for controlling a cooling element associated with an integrated circuit (IC) are described herein. The control system uses the IC's temperature and power consumption as inputs into the control system. By monitoring not only the IC's temperature, but also its power consumption, the control system may predict the amount of heat generated by the IC and cool the IC with more accuracy and efficiency. The present system will be described, for ease of explanation only, in the context of an IC. However, the control system described herein may be used to cool many different electronic components and groups of components such as chipsets, central processing units (CPUs), voltage regulators, storage units, disk drives, input/output devices, and others.

[0018]   Fig. 1 shows an exemplary integrated circuit (IC) configuration with a cooling element, according to an exemplary embodiment. As shown in Fig. 1, an IC (100) requires a certain voltage (V) to operate. Associated with this voltage is a current (I) that is used by the IC (100) in its operation. The power (P) used, or consumed, by the IC (100) can be calculated using the formula $P = V * I$. In other words, the power used by the IC (100) is equal to the product of the voltage and current supplied to the IC (100). The same formula may be used to calculate the power consumed by any electronic component.

[0019]   The voltage and current may be supplied by the system of which the IC (100) is a part. It is important to note that the configuration of Fig. 1 is exemplary in nature and that many other voltage supply configurations are possible. For example, the IC (100) could have multiple voltages. In this case, the consumed power may be computed by using the dominant voltage rail or a function of the different rails as the voltage value (V) in the power formula given above.

[0020]   As shown in Fig. 1, the IC (100) generates heat during operation. For reasons known to one skilled in the art, most of the power consumed by the IC (100) results in heat. Thus, by calculating the power consumed by the IC (100), one can find the approximate amount of heat that is generated by the IC (100). In other words, the amount of

heat generated by the IC (100) is roughly equivalent to the amount of power consumed by the IC (100).

[0021]   Fig. 1 shows that the heat generated by the IC (100) is dissipated by a cooling element (101) according to an exemplary embodiment. The cooling element (101) helps prevent the IC (100) from overheating. If an IC overheats, it may temporarily malfunction or even be permanently destroyed. The cooling element (101) of the exemplary configuration of Fig. 1 is a fan or blower. However, the cooling element (101) may be, but is not limited to, a fan, blower, turbo cooler, heat sink, or a heat spreader, for example. It may be mounted on the IC (101) or it may be located near the IC (101) in an electronic device of which the IC (100) is a part. The cooling element (101) may be powered by the same source that powers the IC (101) or it may have its own power supply.

[0022]   There may be more than one cooling element in a cooling solution for the IC (100). A cooling solution comprises the circuitry and cooling elements that dissipate the heat generated by the IC (100). For example, the IC (100) of Fig. 1 may have a cooling solution that includes a heat sink (not shown) mounted on top of it in addition to a fan or blower (101). The number of cooling elements used in a particular cooling solution will vary depending on the structure and temperature requirements of the ICs that are to be cooled.

[0023]   A cooling element is controllable if its method of operation can be controlled manually or automatically (i.e., with a microcontroller) in response to a changing characteristic of the IC that it cools. The changing characteristic may be the IC's temperature, power consumption, or some other changing characteristic of the IC that is indicative of its changing temperature. If the cooling element (101) of Fig. 1 is controllable, its speed of operation may be adjusted in response to temperature changes and/or power consumption variations the IC (100). A controllable cooling solution that includes a controllable cooling element will be referred to herein and in the appended claims, unless otherwise specifically denoted, as a thermal control system or simply as a control system.

[0024]   Some cooling elements are easier to control than others. For example, cooling elements that may be a part of a thermal control system include, but are not limited to, fans, blowers, and turbo coolers. Most heat sinks, on the other hand, are passive cooling

elements, and are not controllable. However, some heat sinks may be controllable and therefore may be a part of a thermal control system according to an exemplary embodiment.

[0025]   An exemplary thermal control system is shown in Fig. 2. In this exemplary embodiment, the control system is implemented using a closed loop control system. A closed loop control system, as shown in Fig. 2, is one that constantly monitors the output of the cooling element (101) and adjusts it according to any of a number of factors. For example, the control system of Fig. 2 consists of a number of control functions (120) that may be used to adjust a control signal that controls the speed of the cooling element (101).

[0026]   The control functions (120) in Fig. 2 may perform any of a number of functions. The exact functions that they perform will vary as best serves a particular implementation of the control system. Thus, the following explanation of the control functions (120) will serve only as an illustration of some of the many possible functions that the control functions (120) may perform.

[0027]   As shown in Fig. 2, the cooling element (101) is a controllable cooling element (101). For example, the cooling element (101) in Fig. 2 may be a fan or blower that has a tachometer output signal. The tachometer output signal is a measurement of how fast the cooling element (101) is operating. For example, the tachometer output signal may be a measurement of how fast a fan's motor is running in revolutions per minute (RPM). RPM will be used hereafter and in the appended claims, unless otherwise specifically denoted, as an exemplary measure of the speed or level of operation of a cooling element. Other measurements of the level of operation of a cooling element may also be used.

[0028]   The tachometer output signal is input into the control function (120a), as shown in Fig. 2. The control function (120a) may multiply the tachometer output signal by a constant to amplify it before it is sent to the other control functions (120b, c). According to another embodiment, the control function (120a) compares the tachometer output signal with a preset value and adjusts the tachometer output signal accordingly. For example, the preset value may be an ideal RPM value for the cooling element (101). If the tachometer output signal is lower than the ideal RPM value, then a control signal that is output from the control function (120a) is modified so as to indicate to the cooling element (101) to increase its RPM. Likewise, if the tachometer output signal is higher than the ideal RPM value, then the control

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signal that is output from the control function (120a) is modified so as to indicate to the cooling element (101) to decrease its RPM.

[0029]   An alternate embodiment is that the control system of Fig. 2 does not have the control function (120a). In this case, the tachometer output signal is fed directly into the control function (120b) from the cooling element (101).

[0030]   Referring again to Fig. 2, the control function (120a) outputs a control signal. This control signal may be modified by other control functions (120b, c), as will be explained below. After it is modified, the control signal is fed back into the cooling element (101). Thus, the control system of Fig. 2 is a closed loop control system. The control signal controls the operational speed of the cooling element (101). For example, the amplitude of the control signal may be increased to increase the speed in RPM of the cooling element (101).

[0031]   The control signal of Fig. 2 may be any type of control signal that controls the cooling element (101) and will vary as best serves a particular application. One exemplary control signal is a pulse width modulation (PWM) control signal. A PWM control signal varies the on/off duty-cycle of the supply voltage to the cooling element (101) using a drive transistor. In this way, the PWM control signal may efficiently control effective power delivered to the cooling element's (101) motor.

[0032]   Another exemplary control signal is a linear voltage control signal. A linear voltage control signal varies the direct current (dc) voltage applied to the cooling element (101) to vary the cooling element's speed (e.g.; RPM). Varying the dc voltage to some cooling elements, such as fans, changes their RPM somewhat proportionally.

[0033]   Returning to Fig. 2, the control signal output from the control function (120a) is input into the control function (120b). The control function (120b) has another input for a signal comprising a temperature reading of the IC (100) that is being cooled by the control system. This temperature signal may be derived using inline sensing in the IC (100) itself. It may also be derived using many other temperature sensing devices or circuits.

[0034]   The control function (120b) may perform one or more of a number of functions with the control signal and the temperature signal. For example, the control function (120b) may adjust the control signal based on variations in the temperature signal. If

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the temperature of the IC (100) increases, the control signal may be amplified or modified in a way that indicates to the cooling element (101) that it is to increase its RPM. Likewise, if the temperature of the IC (100) decreases, the control signal's amplitude may be decreased or modified in a way that indicates to the cooling element (101) that it may decrease its RPM. In this way, power may be conserved and system noise may be decreased when it is not necessary for the cooling element (101) to be operating at a high RPM.

[0035]   Another exemplary embodiment is that the control function (120b) compares the temperature of the IC (100) to a preset value representing a maximum temperature at which the IC (100) may properly operate. For example, the maximum temperature at which the IC (100) may operate could be 75 degrees Celsius (C). The control function (120b) may compare the IC's (100) actual temperature to this value and adjust the control signal so that the cooling element (101) cools the IC (100) to a temperature lower than the maximum allowable temperature. The control system may also be configured to send a failure signal to the IC (100) or to a system-level control system to shut down the IC (100) if its temperature goes above the maximum allowable temperature.

[0036]   Another exemplary embodiment is that the control function (120b) compares the temperature of the IC (100) with a preset value representing an ideal temperature at which the IC (100) should operate. For example, the ideal temperature at which the IC (100) operates could be 30 degrees C. The control function (120b) may compare the IC's (100) actual temperature to this value and adjust the control signal so that the cooling element (101) cools the IC (100) to a temperature that is equivalent to this ideal temperature.

[0037]   Yet another exemplary embodiment is that the control function (120b) performs a combination of the above-described functions. For example, the control function (120b) could linearly adjust the control signal based on variations in the temperature of the IC (100) while at the same time ensuring that the IC's (100) temperature does not exceed its maximum allowable temperature under which it may operate.

[0038]   After the control signal has been modified by the control function (120b), it is fed into the control function (120c). The control function (120c) also has another input for a power signal comprising a power consumption reading of the IC (100) that is being

cooled by the control system. This power signal may be derived by measuring the input voltage and current of the IC (100) and then using the power formula (P = V * I) described in connection with Fig. 1. The power signal may also be derived using other devices capable of measuring the power consumed by the IC (100).

[0039]   The control function (120c) may perform one or more of a number of functions with the control signal and the power signal. For example, one exemplary embodiment is that the control function (120c) may adjust the control signal based on variations in the power consumed by the IC (100). As was explained in connection with Fig. 1, if the power consumed by the IC (100) increases, the IC (100) produces more heat. Thus, the control signal may be amplified or modified in a way that indicates to the cooling element (101) that it is to increase its RPM if there is additional heat that needs to be dissipated. Likewise, if the power consumed by the IC (100) decreases, the control signal's amplitude may be decreased or modified in a way that indicates to the cooling element (101) that it may decrease its RPM. In this way, power may be conserved and system noise may be decreased when it is not necessary for the cooling element (101) to be operating at a high RPM.

[0040]   Because the control system monitors the power that is consumed by the IC (100) with the control function (120c), the control system may preemptively increase the RPM of the cooling element (101) and dissipate the heat as is produced instead of waiting for the temperature to increase before cooling the IC (100). In other words, monitoring the IC's (100) power consumption enables the control system to predict the amount of heat that will be generated by the IC (100) and accordingly adjust the cooling element (101) to compensate for the increased heat.

[0041]   As shown in Fig. 2, after the control signal is modified by the control function (120c), it is input into the cooling element (101) or into a circuit that controls the cooling element (101). According to an exemplary embodiment, the control signal either speeds up or slows down the RPM of the cooling element (101).

[0042]   An alternate embodiment is that the control system illustrated in Fig. 2 does not have the control function (120b) that modifies the control signal based on the temperature of the IC (100). In this case, the only input from the IC (100) into the control system is the power signal that goes into the control function (120c).

[0043]   The control system illustrated in Fig. 2 may be implemented in multiple ways. Fig. 3 illustrates an exemplary implementation of the control system using a microcontroller (130), according to an exemplary embodiment. As shown in Fig. 3, the microcontroller (130) has three inputs. One of the inputs is the tachometer output signal from the cooling element (101). The other two inputs are the temperature (131) and power (132) readings from the IC (100). The temperature and power inputs (131, 132) may be analog inputs according to one embodiment. However, they may be digital signal inputs according to another embodiment. As shown in Fig. 3, the microcontroller (130) outputs the control signal to the cooling element (101). Thus, the microcontroller (130) performs all of the control functions (120) described in connection with Fig. 2, according to an exemplary embodiment. The microcontroller (130) may be an application specific integrated circuit (ASIC), field-programmable gate array (FPGA), digital signal processor (DSP), or some other type of IC.

[0044]   An alternate embodiment is that the control system may be implemented using analog components for each of the control functions (120). The exact method of implementation using analog components will be obvious to one skilled in the art and will not be explained herein.

[0045]   The control system may be implemented in a system level cooling solution as shown in the exemplary configuration of Fig. 4. As shown in Fig. 4, a system thermal management controller (140) controls a system cooling element (141). The system cooling element (141) may be one or more of any of the cooling elements previously discussed. For example, the system cooling element (141) may be system fans. The system thermal management controller (140) controls the thermal environment of the system of which the IC (100) is a part.

[0046]   As shown in Fig. 4, the IC's control system (130) in this configuration has two outputs. One output is the control signal that controls the cooling element (101). According to one exemplary embodiment, the other output is a two stage alert signal that goes to the system thermal management controller (140). The two stage alert signal may be a signal that performs two functions. The first stage alert request the system thermal management controller (140) to boost fan speed of the system cooling element (141). The

second stage of the two stage alert signal may be a failure signal that requests the system thermal management controller (140) to shut down the entire system due to excessive heat that cannot be dissipated. The two stage alert signal is one of many possible alert signals that may be sent to the system thermal management controller (140). The exact performance requested by an alert signal will vary as best serves a particular application.

[0047]   Fig. 5 illustrates an exemplary embodiment wherein more than one control system and cooling element may be used in combination with a system level cooling solution. As shown in Fig. 5, there are two control systems and cooling elements (151, 152) that are used in combination with the system thermal management controller (140) and system cooling element (141). Although the exemplary configuration of Fig. 5 has two control systems and cooling elements, other systems may have more than one or two control systems and cooling elements, as is readily apparent to one of ordinary skill in the art. As shown in Fig. 5, the cooling elements for the IC (100) and for the chipset (150) are not shown, but are integrated into the control systems blocks (151, 152) for ease of explanation.

[0048]   The two components that are being cooled in Fig. 5 are a central processing unit (CPU) (150) and a chipset (151). A chipset is a group of microchips or ICs that are designed to work as a unit in performing one or more related functions. The CPU (150) and the chipset (151) are examples of many types of ICs that may be cooled in the same system such as input/output (IO) controllers, memory units, etc.

[0049]   Fig. 5 shows that the CPU (150) and the chipset (151) have their own localized cooling solutions. These cooling solutions are in addition to the system level cooling solution. This configuration may be used in low-end systems where the management processing power available is not adequate for babysitting multiple ICs.

[0050]   As shown in Fig. 5, the CPU's control system (152) is configured to send a two stage alert to the system thermal management controller (140). The two stage alert signal is the same as the two stage alert signal described in connection with Fig. 4. The chipset's control system (153) is configured to send only a failure control signal to the system thermal management controller (140) requesting it to shut down the entire system or only the chipset (151). Again, the control signals that are sent to the system thermal management controller (140) may be any type of control signal. For example, the chipset's control system (153) may

be configured to send two stage alert signal to the system thermal management controller (140).

[0051]   Another exemplary embodiment is that a control system for the IC (100) may be created to have rules, or memory. In other words, the control system may be programmed or designed to recognize certain trends in power consumption, temperature variations, or irregular IC or system behavior. By recognizing such trends, variations, or irregular behavior, the control system can maintain an appropriate control signal to a cooling element.

[0052]   Fig. 6 is a graph illustrating power consumption by an IC for which a control system could be created or programmed to have memory. Fig. 6 shows an exemplary IC's power consumption as a function of time. As shown in Fig. 6, between the times t_0 and t_1, there is a short spike (160) in the power consumption that goes above a threshold level. The rest of the time, the power consumption only varies slightly around a normal level. According to an exemplary embodiment, the control system may be created or programmed to ignore a spike (160) in power consumption that goes above a specified threshold if it lasts less than a specified amount of time. For example, the specified amount of time may be 250 milliseconds and the threshold may be 70 watts. In this case, if the spike (160) in power consumption is above 70 watts for 150 milliseconds, then the control loop would ignore the spike (160) and not increase the speed of the cooling element (101) to compensate for temporary increase in power consumption. The specified threshold and the specified amount of time will vary as best serves a particular application.

[0053]   There are a number of applications that may use a control loop with memory for the situation described on connection with Fig. 6. For example, a CPU might process mostly integer numbers. But, occasionally it processes floating point numbers. When the CPU processes a floating point number, there is a spike in power consumption similar to the spike (160) of Fig. 6.

[0054]   According to another exemplary embodiment, the control system may have memory or rules that allow it to selectively ignore variations in power consumption. Fig. 7 is a graph illustrating power consumption by an IC for which variations in the power consumption may require the control system to selectively ignore variations in power

consumption. Fig. 7 shows an exemplary IC's power consumption as a function of time. As shown in Fig. 7, the power consumption varies frequently. In some applications, the cooling element (101) is not capable of changing speeds at the same rate that the power consumption varies. Therefore, according to this exemplary embodiment, the control system may ignore some of the variations in power consumption and use instead use periodic readings of the power consumption as the input into the control function (120c). Fig. 7 shows that the control system uses the values of power consumption at the times t_0, t_1, ... , t_7.

[0055]   An alternate embodiment to that described in connection with Fig. 7 is that the control system selects every n-th variation in the power consumption. For example, if the power consumption varies 50 million times per second, the control system selects every 10 millionth variation to use as the input into the control function (120c).

[0056]   The rules that may be programmed into the control system that have been described above are examples of many different rules that the control system may have. Additional rules may be implemented to recognize other trends in power consumption or in temperature change of an IC as best serves a particular application.

[0057]   Another exemplary embodiment entails using the control system to perform predictive failure analysis. The control system may collect and store in memory data related to the cooling element. This data may be variation in operation speed, amount of power consumed by the cooling element, etc. The control system may then analyze this data and recognize trends that may indicate that the cooling element has a certain percentage of failing after a certain amount of time. The control system may be programmed to recognize these trends and react to them in a number of ways. For example, in one embodiment, the control system reports to a higher entity the existence of these conditions that may predate a failure. Exemplary higher entities may be, but are not limited to, system level thermal management processors and service personnel. An alternate embodiment is that the control system may disable a cooling element that it has determined to have a high chance of failure and enable a backup cooling element in its place.

[0058]   Fig. 8 is a flow chart illustrating a possible method of implementing the present control system with memory according to one exemplary embodiment. The steps of Fig. 8 correspond to the control function (120c; Fig. 2) that has an input for the power signal.

The steps of Fig. 8 may be programmed into the control system. They may also be performed by a processor or another device configured to perform them.

[0059]   As shown in Fig. 8, the initial step is measuring the current power consumption of the IC that is being cooled (180). Next, any rules, or memory, that have been programmed into the control system are applied (181). These rules may be any of the rules that have been already described above. The control system then determines whether the IC power consumption has increased from the previous measurement of the power consumption (182). If it has, the speed of the cooling element is increased (183). If the IC power consumption did not increase, but decreased (184), then the speed of the cooling element is decreased (184). If the power consumption did not increase or decrease, the cooling element's speed may be maintained at its previous rate (186). However, an alternate step (not shown) to step (184) is that if the power consumption did not increase or decrease, the cooling element's speed may be decreased.

[0060]   Fig. 9 is another flow chart illustrating a possible method of implementing the present control system with memory according to one exemplary embodiment. The steps of Fig. 8 correspond to the control function (120b; Fig. 2) that has an input for the IC temperature reading. The steps of Fig. 9 may be programmed into the control system. They may also be performed by a processor or another device configured to perform them.

[0061]   As shown in Fig. 9, the initial step is measuring the current temperature of the IC that is being cooled (190). Next, any rules, or memory, that have been programmed into the control system are applied (191). These rules may be any of the rules that have been already described above. The control system then determines whether the IC temperature has increased from the previous measurement of the temperature (192). If it has, the speed of the cooling element is increased (193). If the IC temperature did not increase, but decreased (194), then the speed of the cooling element is decreased (194). If the temperature did not increase or decrease, the cooling element's speed may be maintained at its previous rate (196). However, an alternate step (not shown) to step (194) is that if the temperature did not increase or decrease, the cooling element's speed may be decreased.

[0062]   The methods described in Fig. 8 and Fig. 9 may be performed simultaneously, according to an exemplary embodiment. They may also be integrated so as to function with system thermal management controller (140; Fig. 5).

[0063]   The preceding description has been presented only to illustrate and describe embodiments of invention. It is not intended to be exhaustive or to limit the invention to any precise form disclosed. Many modifications and variations are possible in light of the above teaching. It is intended that the scope of the invention be defined by the following claims.